beyond the scope of this standard. However, these topics are discussed in other readily-available documents, to which the interested reader is referred.

The following documents contain useful information on the application of surge arrestors, lightning, 60-Hz over voltages, and the loop electrical environment.

ANSI/IEEE C62.42-1986, *Guide for the application of gas tube arrestor low-voltage surge-protective devices*

CCITT Recommendation K.21, *Resistibility of subscribers terminals to overvoltage and overcurrents*[3]

CCITT Recommendation K.22, *Overvoltage resistibility of equipment connected to an ISDN T/S bus*[3]

Lightning, radio frequency and 60-Hz disturbances at the Bell Operating Company network interface. Technical Report TR-EOP-000001, Issue 2, Piscataway, NJ, Bellcore; June 1987

The following document should also be considered:

ANSI/EIA/TIA-571, *Environmental and Safety Considerations for Telephone Terminals.*[2] This proposed standard discusses the normal operating environment of telephone terminal equipment, as well as fire hazards and protection.

The reader may also wish to consult:

Batorsky, D.V., and Burke, M.E., 1980 *Bell System noise survey of the loop plant*, AT&T Bell System noise survey on the loop plant, AT&T Bell Laboratories Technical Journal 63(5): May-June 1984.

Bodle, D.W., and Gresh, P.A., *Lightning surges in paired telephone cable facilities*. Bell System Technical Journal 40: March 1961

Carroll, R.L., *Loop transient measurements in Cleveland, South Carolina*. Bell System Technical Journal 59(9): November 1980

Carroll, R. L., and Miller, P. S., *Loop transients at the customer station.* Bell System Technical Journal 59 (9): November 1980

Clarke, Gord, and Coleman, Mike, *Study sheds light on overvoltage protection*. Telephony: November 24, 1986

Gresh, P.A., *Physical and transmission characteristics of customer loop plant*. Bell System Technical Journal 48: December 1969

Heirman, Donald N., *Time variations and harmonic content of inductive interference in urban/suburban and residential/rural telephone plants*. IEEE, 1976 Annals No. 512C0010

Koga, Hiroaki, and, Motomitsu, Tamio, *Lightning-induced surges in paired telephone subscriber cable in Japan*. IEEE Transaction Electromagnetic Compatibility EMC-27: August 1985

Measurement of Transients at the Subscriber Termination of a Telephone Loop, CCITT, COM V-No. 53: November 1983

The power emitted by transmitters is limited by the masks specified in T1.403.

Notwithstanding any information contained or implied in T1.403, it is assumed that the equipment supporting the interface specified in this standard will comply with applicable FCC requirements on emission of electromagnetic energy. These requirements may be found in the Title 47, Code of Federal Regulations, parts 15 and 68, and other FCC documents.

In the design of equipment, consideration should be given to the handling of the following additional environmental conditions:

Ringing voltages can be applied accidentally to the interface conductors. The typical ringing voltages are 88 V RMS at 20 Hz superimposed on –52 V dc. Higher voltages exist that use multi-frequency ringing to a large degree. The ringing voltage in use in the 55-Hz through 67-Hz range can be as high as 155 V RMS. This voltage can appear superimposed on –57 V of battery feed voltage in some systems, for a total of 276.2 V peak. Ringing cadences typically have a 33-% duty cycle over a 6-second period.

Annex B
(informative)

Bibliography

CCITT Recommendation M.3602 (10/92), *Application of maintenance principles to Integrated Services Digital Network subscriber installations*[8]

CCITT Recommendation M.3604 (10/92), *Application or maintenance principles to Integrated Services Digital Network primary rate accesses*[8]

[8] Available from American National Standards Institute, 11 West 42nd Street, New York, NY 10036.

Lucent Technologies
Bell Labs Innovations

PERFORMANCE OF HIGH SPEED MODEMS OVER THE PUBLIC SWITCHED TELEPHONE NETWORK

LUCENT TECHNOLOGIES
JANUARY 1997

10084

Questions regarding this document can be referred to the following Lucent Personnel:

Gerry Boyer 201-386-4422
Phil Goelz 201-386-7499

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Lucent Technologies

Performance Of High Speed Modems Connected Over The Public Switched Telephone Network

Executive Summary

Expanding interest in Internet communications and work-at-home has stimulated development of standard V.34 voice frequency modems capable of achieving connect rates of 28.8 kb/s, with newly extended capabilities up to 33.6 kb/s.

This paper discusses the factors that influence modem connect rates, including the impact of various network technologies and the thresholds at which achievement of the highest rates become questionable. It concludes with recommendations for both telephone network evolution and Internet Service Provider (ISP) connections to the telephone network, in particular recognizing the significant impact of next generation 56 kb/s modems expected to become available in 1997. (Note that the work-at-home application is similar to the internet application, with the business enterprise replacing the ISP end of the connection.)

Data Throughput Problem

The voice frequency (VF) modem connect rate achieved on a given dial-up call between an end data user and an ISP over the Public Switched Telephone Network (PSTN) depends on a complex interrelationship of the five following independent elements:

1) end user modem type,
2) access technology/media connecting the end user to his serving PSTN switch,
3) the specific dial-up connection path through the PSTN,
4) access technology/media connecting the ISP to his serving PSTN switch, and
5) ISP modem type.

Though a given PSTN dial-up connection and respective user and ISP access links will be perfectly acceptable for voice communication, they may present a variety of "impairments" to high speed V.34 modems, which are pushing the theoretical limit for such a band limited voice channel.

To further complicate the problem from a user's perspective, the modem connect rate, indicated by the modem (also called the "DCE rate") may not accurately reflect the actual data throughput. Compression algorithms can substantially increase throughput for certain kinds of data, but transmission errors associated with a modem selecting a too aggressive connect rate can substantially decrease throughput due to retransmissions of errored data blocks.

Modem Variability

V.34 modems employ a variety of sophisticated transmission techniques, including automatic equalization, echo cancellation, baud selection, QAM constellation selection and trellis coding, to overcome impairments presented to analog signals. Modems attempt to overcome these impairments to connect at their highest rates on a given call. While most modems will likely function at their maximum rates over two relatively short, directly connected metallic loops (of reasonable quality), they may differ dramatically when additional impairments are added, depending on how vendors have chosen to implement the V.34 standard (particularly in receiver design and rate selection algorithms).

These network "impairments" can generally be characterized in terms of two measures associated with the received signal, 1) **absolute signal level** and 2) **signal to noise ratio**, measured at the extreme frequencies of interest. For connect rates of 28.8 - 33.6 kb/s, the critical frequencies correspond to about 200 - 3700 Hz. (Note that most transmission parameters characterizing the PSTN for voice quality are measured down at 1004 Hz.) Receive signal values at which V.34 modems may fail to connect at their highest rates are generally between **-40** and **-45 dBm** signal level and less than **36 dB** signal to noise ratio.

<u>Impairments In The PSTN and PSTN Access Links</u>

The most challenging network connections involve at least one high loss metallic pair and/or two or more digital links, where each digital link is defined as a paired A/D (analog to digital) and D/A (digital to analog) conversion. High loss metallic pairs are considered to be greater than 12 kft in working length and may have load coils or significant lengths of bridge tap.

Telecommunications Systems Bulletin 37A for V.34 modems is based on the last available Bell System loop survey from 1983, which includes a significant number of long, as well as some loaded, loops. It recognized the digital evolution of the PSTN switching and interoffice network, but not today's significant deployment of Digital Loop Carrier (DLC) in the access links which are estimated to be approximately 20% of total loops. Note that the maximum length of the metallic pair beyond a DLC Remote Terminal is limited by Carrier Serving Area rules to 12 kft or less. We estimate in this paper that DLC deployment has effectively reduced the population of challenging high loss metallic pairs from roughly 11% to 2%.

At the same time, when deployed in a "Universal" rather than an "Integrated" configuration, DLC systems introduce an additional digital link. Each independent digital link presents at least three types of impairments to a V.34 modem,

1) quantization noise from representing the continuous VF signal in discrete mu-law coding steps,
2) echo at the D/A point due to impedance mismatch of the 4-wire to 2-wire hybrid with the subtending pair, and
3) band edge roll-off of anti-aliasing filters associated with both transmit and receive CODECs.

The incidence of Universal DLC systems today is estimated to be about one half (for an average LEC) of total DLC loops, bringing the likelihood of encountering a challenging user access link on a statistical basis back to about 10% of total lines.

Robbed bit signalling associated with the TR-08 and TR-303 integrated DLC interface standards, represents the only other significant digital impairment. Additional forms of PSTN digital impairments are discussed in the paper, but are not considered to be chronic problems since they are associated with either "long distance" calls, improper network design, or special VF access services. Respective examples include digital loss pads for controlling echo or "voice enhancement" equipment not properly disabled by modem start-up tones, T-carrier systems improperly synchronized to network clock or displaying a high bit error ratio, and Foreign Exchange service when "groomed" through a narrow band Digital Cross-connect System (DCS). ←1 by O

The PSTN access network is a complex collection of cables, cross-connect points and electronics that has evolved over many years, using equipment from many suppliers and based on a variety of plant designs that were intended to meet voice quality objectives and minimize overall cost. The particular local loop for a given residence or small business is randomly assigned by the Local Exchange Carrier (LEC) and its makeup depends on user location relative to the serving switch in his "wire center" area and generally on the plant engineering strategy employed by the LEC in that area.

While the typical telephony user has no control over his access facility, the ISP is an information access business and should have an incentive to provide the best possible connection environment for modem performance. Many ISPs today connect to the PSTN just like an ordinary end user, with ordinary telephone loops and 2-wire consumer modems. However, alternatives like premises mounted channel banks can effectively shorten the ISP's metallic loop and an all-digital access service (like ISDN) terminating in specialized 4-wire digital modems can eliminate the last D/A conversion and hybrid entirely.

Note also that ISPs can reduce the likelihood of certain impairments associated with long distance calls by increasing their density of POPs (Points Of Presence), so that dial-in users are making only "local" modem calls.

New 56 kb/s Modems

A new approach for VF modems is expected to be standardized soon and will likely become the norm for consumer modems. These modems take advantage of the digital mu-law coded nature of the PSTN to achieve rates toward the user of about 56 kb/s. Their operation is predicated on

1) <u>one and only one A/D conversion occurring in the PSTN</u> between the user and the ISP,
2) <u>ISPs utilizing an all-digital 4-wire access service</u> and
3) <u>ISPs utilizing specialized mu-law digital modems</u>.

If unable to connect at rates approaching 56 kb/s, these modems will revert to V.34 operation.

Recommendations for Improving Analog Modem Connect Rates

The PSTN access network in the US represents an investment of greater than $100 billion. It will not, and can not, change rapidly. However, to support the highest V.34 rates and enable the forthcoming 56 kb/s rate, the evolutionary goal for the network should be an all-digital PSTN, with a single A/D point as close to the user as possible.

Thus, it is recommended that LECs continue to effectively "shorten" the population of metallic loops by continuing to deploy DLC in its integrated form. LECs can also deploy integrated broadband Fiber To The Curb and Hybrid Fiber Coax networks, both of which effectively reduce the user's 2-wire loop to zero length by moving the A/D point adjacent to the residence.

Concurrently, LECs should consider integrating existing Universal DLC systems whenever a local digital switch is implemented in the local wire center, in order to eliminate the extra digital link and its accompanying impairments.

ISPs also have a very significant role and responsibility for enhancing modem performance. They should utilize an all-digital PSTN access service, such as ISDN (Integrated Services Digital Network) Basic or Primary Access, and terminate this access in a digital modem pool. This is generally required to enable the highest V.34 rate of 33.6 kb/s and will be <u>essential</u> in achieving future 56 kb/s operation.

Finally, it has been observed in laboratory tests that consumer V.34 modems differ significantly in performance when presented with the myriad of analog and digital "impairments" routinely found in the PSTN. The most obvious step an end user can take is to purchase a quality modem from a supplier of good reputation. Businesses should be cognizant of digital key systems and PBXs (Private Branch Exchanges) with analog trunk interfaces because they introduce an additional digial link. A separate, directly wired, line is recommended in these cases for high speed modems and fax machines. Any desire on the part of the user for Internet access beyond 56 kb/s rates will have to be fulfilled by purchase of a specialized digital access service such as ISDN.

TAB 2

HIGH SPEED MODEM PERFORMANCE OVER THE PSTN

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High Speed Modem Performance Over The PSTN

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1. Introduction

Internet usage has increased the demand for higher data throughput speeds between end user modems and Internet Service Provider (ISP) equipment. The Public Switched Telephone Network (PSTN) is, and will continue to be, the dial up connection vehicle between internet users and ISPs. Increasing modem speeds have also brought to the forefront the need to re-examine how the composition of today's dial-up network affects modem performance. The rate at which voice band modems are approaching theoretical transmission limits is such that, in the near future, many modems will be capable of 56kb/s connect rates. As the network evolves to an all digital network, the impact of multiple digital to analog conversions on modem performance must be addressed.

The technical issues surrounding V.34 [1] (the newest generation of standard high speed modems) and emerging 56kb/s modem technology are only parts of an end-to-end performance picture. Also to be considered are variabilities in end user access technologies, ISP connect methods and modem designs. It is therefore imperative to estimate the level of modem performance in the context of these variables. This document provides insight into the V.34 modem performance that can be expected across today's PSTN.

2. Modem Applications

There are three modem applications:

- Internet Access
- Work at Home and
- End User to End User

The dominant modem application is internet access by residential and small business end users. The corporate dial in application for "work at home" is second, followed by the end user to end user modem application. The focus of this document is internet access, however, all modem applications are addressed, in some form, by this information.

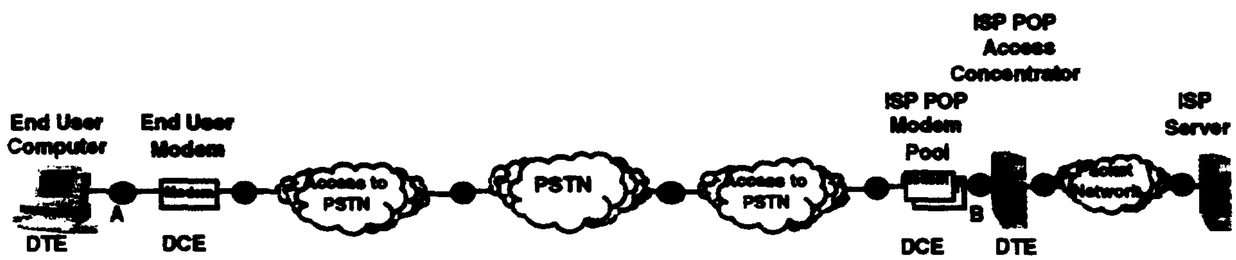

Figure 1: Modem Internet Application Reference Diagram

Figure 1 shows a complete connection from an end user to an Internet Service Provider (ISP). The connection starts with a personal computer or internet appliance and a modem connected to the PSTN via an access facility. A dial-up call across the PSTN reaches the ISP through a second access facility. The ISP Point of Presence (POP) has the modem pools and an access concentrator which converts the dialed connection from the PSTN circuit switched world to a packet network which is more suited for the transport of bursty data traffic.

The service end of the connection is typically located at an ISP premises or Packet Network Carrier's premises. It is responsible for connecting the end user data signal to a data network. In many cases, the end user and ISP modems are both 2-wire modems since the norm for PSTN access is a 2-wire loop. Well designed V.34 modems are capable of two-way simultaneous transmission at a rate of 28.8 kb/s on most connections.

The "work-at-home" application is similar to the internet application but the corporation replaces the ISP in Figure 1; whereas the PSTN simply connects a second end user in the "end user to end user" application. ISPs and corporations have financial incentives in choosing the physical location of the POP(s) and the type of access facilities that connect a POP to the PSTN. An end user in voice band dial-up situations gets, from the local exchange carrier, whatever access facility happens to be available at his location.

3. The Public Switched Telephone Network

Figure 2 lists types of network equipment associated with the PSTN and PSTN access.

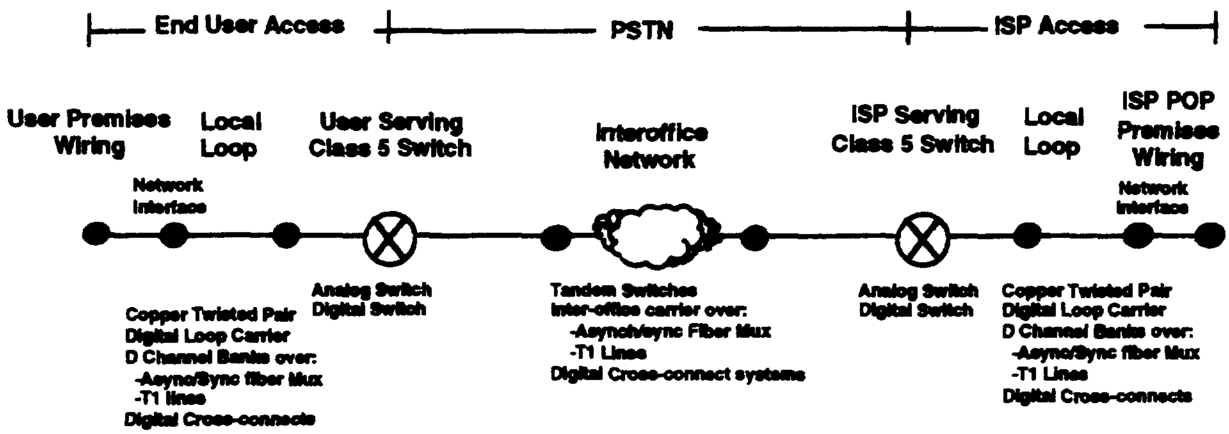

Figure 2: PSTN Reference Diagram And Embedded Equipment

3.1 Access to the PSTN

Access is defined as the connection path from the modem to the serving switch. In this context, it includes premises equipment, premises wiring and the local loop. Customer wiring and customer premises equipment, such as key systems and Private Branch Exchanges (PBX), can introduce additional transmission impairments, over and above those that may be encountered within the

PSTN. For example, digital key systems and PBXs may use analog connections to the serving class 5 switch in which case an additional conversion from digital to analog (and visa versa) is introduced. The variations of equipment types, wiring schemes (and potential premises wiring problems) are beyond the scope of this paper.

The local loop is typically the only analog portion involved in an internet connection. Plain Old Telephone Service or "POTS" (termed "RJ-11 permissive jack" by the FCC) is most commonly used for end user modem connections to the PSTN. POTS circuits are "non-designed" meaning that there is no special consideration given to the transmission properties of the circuit. In the business world, a POTS line is called a "Measured Business Line" or 1MB. ISPs use 1MBs to gain access to the PSTN. Except for billing, 1MBs have exactly the same attributes likely to be found on a residential POTS line.

Telephone companies typically make no guarantee relative to the performance of these circuits except that "voice will work". Access services are available that are guaranteed to have certain transmission attributes (no load coils and no bridged tap) and may even specify the maximum supported DCE rate. Some telephone companies guarantee modem DCE connect rates up to 9.6 kb/s on specially designed access circuits. Digital access services include Basic and Primary Rate ISDN, Digital Data Service and DS-1 connections, which are more expensive than POTS lines. Such access connections might be employed by an ISP or corporation.

A loop is a single twisted wire pair comprised of one or multiple wire gauges ranging in length from a few hundred feet to over six miles. Most loops include "bridged taps" which allow the same pair to electrically appear at multiple locations. Loop quality varies with the age of the plant, the technology used at installation and, in many cases, how frequently maintenance has been performed since its initial installation (e.g., splices redone, pairs moved in terminals, cable section replacement etc.). Most of the loops over 18 kft long are conditioned to improve voice service by the addition of load coils which limit the bandwidth but help to maintain a flat response over the 3200 Hz voice frequency band (these loaded loops will not pass digital services such as ISDN because they operate above the load coil passband). Each end user's loop differs in terms of length, gauge, bridged tap, loading etc. and the statistical characterization of all loops is referred to as the "loop population".

Digital Loop Carrier systems (also called Pair Gain systems) were developed to recover wire pairs where cable capacity was exhausted. They are also deployed to electrically shorten longer loops thereby increasing the quality of the connection. DLC systems effectively reduce the length of the copper loop by placing remote digital electronics closer to the customer. Early DLC systems used digital T-Carrier facilities on copper pairs and were all "Universal" meaning that another terminal needed to be located in the Central Office (CO) to convert the digital signal back to analog before connecting to a switch. These systems were first introduced in 1971[2]. Universal systems are still in use but standardization of high speed digital switch interfaces has reduced the need for this capability. Integrated DLC systems using the TR-08 [3] interface for digital switches, followed in 1984, eliminating the need for a Central Office Terminal (COT).

DLC systems are usually implemented under Carrier Serving Area (CSA) design rules which were developed to target more troublesome areas beyond easy reach of a copper pair. CSA design also stipulated geographic limits and other OutSide Plant (OSP) practices to assist engineers in laying out the plant. CSA design stipulates that CSAs begin between 12 and 18 kft from the office and that they maintain no more than 12 kft lengths of metallic pairs from the remote electronics to the end user. In some cases, these rules have been violated. For example, if a new wire center were created and an area transfer took place, loops that were longer than 18 kft and loaded may now be shorter than 18 kft but the load coils may never have been removed. This would result in short, loaded, loops that would not perform as well as a non-loaded loop of the same length.

Today, DLC systems are used for reasons other than improving transmission performance. Quite often, they are deployed to relieve copper cable congestion closer to the CO. Placing a DLC system far out in the access network and rolling service onto it frees up copper pairs all along the path from the CO to the remote terminal. This relief strategy has helped many Local Exchange Carriers (LECs) delay placements of new feeder cable. DLC systems can also provide lower cost and faster provisioning of telephony in higher density residential areas and business locations by reducing the amount of physical plant needed. DLC is also used to "rehabilitate" aging plant and to provide new services such as ISDN.

3.2 The PSTN

The PSTN switching and interoffice network, as with the access plant, is a mixture of various technologies. Analog and digital switches provide the features and services to end users. Switches are interconnected primarily with digital trunks but some analog trunks are still in service. Local Exchange Carriers (LECs), in recent years, have converted many switches from analog to digital. The end user's serving switch is not always located within the end user's local Central Office. Foreign Exchange and Off Premises Extensions are switched special access services that traverse the interoffice network via D type channel banks that home on a remotely located switch. "D" type channel banks incorporate the same technologies commonly found in DLC remote terminals.

Switches are inter-connected by Inter-Office (I/O) facilities. The interoffice network began migrating to digital facilities in the 1970s and is almost all digital. The digital inter-office network also contains various vintages of transmission equipment and facilities[1].

3.3 Local and Long Distance Services Service Providers

A number of network providers can provide local and long distance access services under the umbrella of the PSTN, including Inter-exchange Carriers, Competitive Local Exchange Carriers (CLECs) and Competitive Access Providers (CAPs). These new entrants in the local exchange business will likely add more diversity to the types of access possible.

[1] The term "facilities" used here refers to the physical and transport media used to connect individual circuits between switches. They may be copper, fiber or digital radio.

Unbundling is a result of de-regulating the Local Exchange Carrier (LEC) access network. It requires the LECs to "open up" the access network to CLECs by providing access to individual subscribers at various points in the network. Subscribers that are served by a cable pair or Universal DLC can be accessed via the Main Distributing Frame (MDF). Competitive access for subscribers served by Integrated DLC (IDLC) is a more complex situation since the individual subscriber DS0 does not appear at an easily accessible demarcation point such as the MDF. Unbundling of LEC local loops for CLEC use may impact modem performance, particularly if integrated DLC systems must be (partially) converted to universal configurations with "tip" and "ring" appearances on the LECs Main Distributing Frame.

Finally, introduction of broadband networks that include telephony by LECs and Cable TV companies should improve modem connect rates and offer customers higher speed access to the PSTN.

3.4 End to End Data Throughput Across the PSTN

The most meaningful modem performance measure is data throughput. Throughput is defined as the time (stated in seconds) it takes to transfer a data file (stated in number of characters) and is commonly measured in characters per second (cps). In figure 1, this path is from A to B or B to A.

Along a dial-up connection path, there are a great number of variables. Network planners have incorporated many technologies to improve the transmission characteristics of the network. Over the past 100 years, nearly all of these improvements were designed to enhance and improve voice grade communications (typically, the transmission attributes of the PSTN are characterized and optimized at 1004 Hz). These improvements are not necessarily optimal for high speed modems which use frequencies ranging from 200 to 3700 Hz.

While DCE connect rate (see section 4) is a rough indication of data throughput, in reality the actual throughput can only be determined by measuring the time it takes to transfer a file. Data throughput is controlled by modem DCE rate, error rate, retransmission block size, compression, network processing delays and server delays.

For example, servers can be bogged down processing other requests and packets can experience transit delays across packet networks. If routers are used in packet networks, destination addresses have to be reprocessed at each node. This reprocessing introduces delay. Variable delay is introduced as congestion increases. Full blown packet switches can decrease the delay because they process the addresses only once, to set up a logical path at the beginning of the call. No significant additional processing is required until the call is torn down thus decreasing the overall delay.

4. Voice Band Modem Tutorial

4.1 Bits, Bytes, Baud and Blocks

This section provides a quick review of several digital concepts which are fundamental to modem operation. The "bit", representing one of two states (e.g. 0 or 1), is the basic unit of digital data. Most interactive services utilize the asynchronous data transmission mode and American Standard Code for Information Interchange (ASCII) format to specify keyboard characters. Characters are typically represented by an 8 bit byte and a start and stop bit. With 8 information bits (a byte) there are 2^8=256 possible characters but only the printable subset of these is typically used. V.34 modems are designed to maximize the data throughput and DCE connect rate over connections through the PSTN.

A PSTN connection can be viewed as a communications channel with a bandwidth limited to approximately 3450 Hz. This bandwidth allows a maximum modem analog (line) transmission rate of 3429 symbols per second (sps). The number of symbols per second can also be referred to as baud.

If each symbol represents one bit then the maximum DCE connect rate is 3429 bits/sec (in this case 1 bit/sec=1 baud). To increase the DCE connect rate, high speed modems employ more complex modulation/demodulation schemes in which each symbol represents multiple bits. For instance, in 16 state Quadrature Amplitude Modulation (QAM) four bits are associated with each symbol (= 2^4 or 16 possible states), thereby increasing the maximum possible DCE connect rate of the PSTN channel to 4 x3429 =13,716 bits/sec.

To assure error-free transmission high speed modems use error correction protocols. The most common protocol uses a "block" retransmission scheme. The block length may be varied but is typically 1000 bits long. This block is transmitted along with a Cyclic Redundancy Check (CRC) computed for the data block. If the recomputation of the CRC for the received block indicates an error, the block is retransmitted, which reduces the effective throughput.

4.2 DCEs and DTEs

Modem standards typically use the terminology "DTE" and "DCE." Referring back to Figure 1, the end user modem on the left receives digital serial data from the end user's computer or Data Terminal Equipment (DTE) and converts the digital information to an analog signal to be sent over the local loop. Note that the DTE could be a Personal Computer, Internet Appliance or a file server. The "DTE rate" is the bit transmission rate between the computer and the modem. The Data Circuit-terminating Equipment (DCE) or modem is responsible for providing the conversion to an analog signal necessary for transmission over the PSTN. The "DCE rate" is the bit transmission rate of the modem's data pump.

Throughout this paper, when "connect rates" are discussed, reference is made to the DCE rate of the modem. Most modems can be programmed to display the "connect" rate on the screen of the PC. In addition, the "connect" message can be programmed to reflect the DCE or DTE rate. DTE rates can be very different from DCE rates. In fact, PC terminal emulator software for high speed modems allow the user to set the DTE rates much higher than the maximum DCE rate. This effectively allows the modem to select the best connect rate and use compression (i.e., V42bis) when possible.

4.3 Modem Standards

Full duplex (simultaneous bi-directional data transmission), 2-wire, modem designs for the switched network have changed dramatically since their introduction. Prior to 1973 the highest DCE connect rate was 300 bps achieved with frequency shift keying modulation. To achieve full duplex data transmission the modems used frequency division multiplexing (FDM) techniques. The call originating modem used a center frequency of 1170 Hz and the answering modem used a center frequency of 2125 Hz. To allow simultaneous bi-directional transmission in the presence of network echo suppressors, the echo supressors recognize the 2225 Hz answer tones and disable themeselves. Up to this time the data transmission market was the exclusive territory of the Bell System. The 1968 Carter Phone decision opened the modem (and other customer premises equipment) market to competition. In 1973 a higher speed (FDM) modem design was introduced using a differential phase shift keying (DPSK) modulation technique to increase the DCE connect rate to 1200 bps. The first design was non-standard but in 1978 the CCITT V.22 modem standard was issued and the 1200 bps rate remained the maximum duplex PSTN DCE connect rate until 1982 when the CCITT V.22bis 2400 bps modem standard using FDM, Quadrature Amplitude Modulation (QAM) was introduced. Error correction by retransmission and data compression algorithms were also introduced at this time and provided error free peak data throughput of up to 960 characters per second (9600bps/10 bits/character).

In 1984, prototypes of a new duplex PSTN modem design appeared. These modems were designed to provide duplex 9600 bps DCE connect rates using QAM and echo canceling techniques as defined in the CCITT V.32 modem standard. The line signals use the full bandwidth but are differentiated by unique data scrambling codes (specified in the V.34 standard) for the two directions of transmission. The modem standard was written with the assumption that network echoes exist only at or near the ends of a PSTN connection. At the same time the PSTN was switching from network echo suppressors to network echo cancelers (NECs). To prevent undesirable interaction between NECs and modem echo cancelers the NEC had to be designed to allow disabling by the modem start-up procedure. Thus, the CCITT V.25 call setup protocol standard was modified by adding periodic 180 degree phase reversals to the 2100 Hz answer tone of echo canceling modems. In 1990 the V.32 standard was updated to increase the maximum DCE connect rate to 14,400 bps resulting in the V.32bis standard. At the same time work began in the CCITT Study Group 14 to generate a new PSTN modem standard that was initially dubbed V.FAST (V.LAST by some for "last" voice band modem standard). This standard was to include every technique known to man to arrive at the most flexible and robust modem standard. The effort took four years and resulted in the V.34 modem standard published in 1994.

This standard was the first to dynamically adjust for bandwidth limitations. It is useful to keep in mind that modem standards specify the characteristics of the transmitted signal and only partially deal with the receiver. This allows manufacturers some leeway in designing receivers that may improve transmission. Choices made in the receiver are based on the current understanding of PSTN parameters discussed in this paper. A good receiver design based on knowledge of the range of electrical characteristics encountered in the PSTN will implement techniques that can dramatically improve data transmission rates.

Previous generation V.32 and V.32bis standard modems operate at a fixed carrier frequency of 1800 Hz, a fixed symbol rate of 2400 baud and maximum DCE connect rates of up to 14.4 kbps. The V.32 and V.32bis standards include forward-acting-error-control using trellis-coding. In addition, most high speed modems incorporate an "error correction by re-transmission" protocol (MNP-5, V.42, V.42bis, etc.). V.42bis also includes a compression algorithm that allows a peak DTE rate of up to 4 times the maximum DCE connect rate (4 X 14.4 = 57.6 kbps). Recall that only the DCE connect rates (modem to modem connect rates) are addressed here. V.32 and V.32bis modems provide BLock Error Rates (BLERs) of 0.01 or less at their maximum DCE connect rates of 14.4 kb/s on nearly 100 percent of domestic PSTN connections.

ITU (International Telecommunications Union) V.34 standard modems are designed to provide DCE rates up to 28.8 kbps and were introduced in 1994. V.34 modems are more sophisticated than previous echo canceling modems and can adapt to more transmission parameters. However, the authors of the V.34 standard were fully aware of the fact that the maximum DCE connect rate of 28.8 kb/s would not be attained on all PSTN connections. The intent of the standard was to describe a modem that would automatically achieve the highest possible DCE connect rate on a given connection. It was also expected that the V.34 DCE connect rate would always be equal to or higher than that achieved by previous generation modems. The V.34 modem standard permits operation with asymmetric (different receive and transmit) DCE rates. A history of CCITT/ITU standard duplex PSTN modem development and some of their characteristics are included in Table 1 below:

Table 1: History of CCITT/ITU Duplex PSTN Modem Standards

Modem Standard	Max DCE Rate	Transmission Scheme	Symbol Rate
V.21	300 bps	FDM/FSK	<300
V.22	1200 bps	FDM/DPSK	<600
V.22 bis	2400 bps	FDM/QAM	600
V.32	9600 bps	EC/QAM	2400
V.32 bis	14,400 bps	EC/QAM	2400
V.34	33,600 bps†	EC/QAM	2400-3429

Note: "EC" in the table above refers to "Echo Cancellation".
† 31.2 and 33.6 kb/s DCE connect rates at 3429 baud are optional in V.34.

ITU standard echo canceling modems were developed with certain assumptions about the PSTN. TIA (Telecommunications Industry Association) TSB37-A[2] [4] describes a large number of simulated PSTN connections. It contains seven local loop models that are based on the 1983 Bell System Loop Survey [5]. The survey data is over 13 years old and does not include loops served by DLC systems. The survey also included only Bell System loops (i.e., no independent Telephone Companies). Still, the 1983 loop survey remains the only comprehensive source of information regarding the statistical loop population in the United States.

4.4 V.34 Modem Operation

V.34 modems use signal constellations containing 4 to 1664 points (at 2400-3429 symbols per second this equates to 2-10.7 bits/symbol). The number of bits represented by each symbol is determined dynamically by both modems after agreeing on the condition of the channel that interconnects them. At start-up, the modems go through a training phase using a series of 21 probing tones. The training phase allows two modems to agree on a base set of operating parameters which will be used during the call. The ITU V.8 [6] standard specifies that the modem should wait between 1.8 and 2 seconds to allow time for old billing systems to start. It would be prudent for modem manufacturers to honor this time period in order to allow network elements (i.e., adaptive electronic hybrids) time to adapt.

During modem training, results of the modem's measurements are used to select the optimum symbol rate and carrier frequency to take maximum advantage of the available bandwidth. Symbol

[2] TSB37-B is being generated at the time of this writing. It extends the PSTN loop plant models to include DLC systems and specifies stronger network echoes.

rates of 2400, 2743, 2800, 3000, 3200 and 3429 baud are available. At each symbol rate (except 3429 baud) a low and high carrier frequency is also available. The modem DCE connect rate is also selected based on the signal to noise ratio. After the modem enters the full duplex mode it can further optimize the DCE connect rate in 2.4 kb/s steps ("rate re-negotiation") based on the signal quality (Mean Squared Error - MSE) of the demodulated receive signal. The MSE characterizes the variation of the actual received signal point constellation from the theoretical amplitude and phase prediction and is a direct function of the Signal to Noise Ratio (SNR). The word "Noise" includes random and signal dependent noise.

The MSE for an acceptable (typically 1 percent) BLock Error Ratio (BLER) at each DCE rate is determined in laboratory tests, placed into modem memory and used by the modem during and/or after startup to optimize the DCE connect rate. A V.34 modem's margin against noise and/or distortion must be the highest at the maximum symbol rate and vice versa. Each modem manufacturer has the freedom to select the BLER where switching to a higher/lower DCE connect rate occurs. In addition, V.34 modems employ adaptive transmit signal pre-emphasis, trellis coding, pre-coding, frame switching, constellation shaping, shell mapping, nonlinear encoding and transmit power control algorithms to mitigate the effects of dynamic and/or steady state distortions. Without these capabilities V.34 modems would not be able to support DCE connect rates up to 28.8 kbps and certainly would not support 33.6 kb/s.

Modem output levels are regulated by the FCC and must be -9 dBm or less. This level is the 3 second average measured into a 600 Ohm terminating impedence. Most modems operate at -10 dBm, allowing 1 dB of margin. Typical modem receivers operate down to receive levels between approximately -40 to -45 dBm. These levels are RMS (Root Mean Squared) values across the entire modem's output spectrum. Recognizing that attenuation is worse at higher frequencies, better modems use pre-emphasis to boost the energy at higher frequencies. Manufacturers are however, careful to maintain the -9 dBm RMS limit set by the FCC.

4.5 Modem Throughput

As discussed in section 3.4, the most important data transmission criterion is throughput (data transfer rate = file size in characters divided by transmission time in seconds - characters per second or cps). The data throughput without (modem internal) data compression is limited to 25% above the DCE rate because the start and stop bits are stripped from each 10 bit ASCII character at the transmitter and reinserted at the receiver. At a DCE connect rate of 28.8 kb/s, the maximum throughput without compression is therefore 1.25 (10/8) X 2880 or 3600 cps. At a DCE connect rate of 28.8 kb/s a well designed V.34 modem should achieve a data throughput of 3400+ cps.

The TIA standards organization has published a Telecommunications Systems Bulletin TSB38-A "Test procedures for Evaluation of 2-wire Duplex Modems" [7] that describes a throughput measuring technique using several file types. This technique provides the most meaningful modem performance results. Simply observing modem "connect" rates can be misleading. Laboratory tests with many V.34 modems have shown that higher than optimum connect rates are sometimes selected. For example, on a given connection a modem connected at a DCE rate of 28.8 kbps (3429 baud). The error rate was excessive and the throughput was only 2500 cps. The modem was then forced to use a symbol rate of 3200 baud by the operator and connected at only 26.4 kbps but, due to a lower error rate, the throughput increased to 3000 cps. The modem selected the highest symbol rate during the half duplex training phase. Severe envelope delay distortion at the band edges resulted in dispersed echoes with post cursors that fell outside of the modem's echo canceler span at a symbol rate of 3429 but not 3200. Some V.34 modems initially connect at a high DCE rate and later fall back to a lower rate. Some modems initially connect at a low rate and then fall forward to a higher rate. The rate changes are usually transparent to the user because in most applications the customer's communications software sets the (DTE) rate to four times the maximum DCE rate (4x9.6=38.4; 4x14.4=57.6; and 4x28.8=115.2 kbps)-effectively allowing the modem to control the DCE rate. This is why the throughput measurement provides the only meaningful results.

Error rates are an important aspect of data communications via analog modems. The time varying nature of impairments can make the choice of retransmission block sizes an important parameter. Selecting a retransmission block size that optimizes throughput on a given connection is a complex process. Large retransmission block sizes are more appropriate for environments where sporadic impulse noise is the only concern. If an impulse strikes infrequently, then a higher throughput can be achieved by sending larger blocks since the overhead is lower. With lower level random noise, smaller block sizes are better since the chances of obtaining an error free block are higher. When retransmissions occur, it is better to resend the shortest block possible.

4.6 Modem Sensitivity to Signal to Noise Ratio (SNR)

Transmission impairments from the PSTN can generally be characterized in terms of SNR. To get a notion of how modem performance is affected by SNR, the relationship between SNR, symbol rate and connect speed needs to be understood. Table 2 lists the SNR requirements of a well designed V.34 modem operating at a typical receive level on a flat channel with random noise only and the corresponding bandwidth requirements for each symbol rate. The gray areas list connect rate/symbol rate combinations that have been added to the V.34 specification at the October, 1996 ITU meeting.

Table 2: Measured V.34 Minimum SNR (dB) vs. Connect Rate (kb/s) and Symbol Rate (sps)*

SYMBOL RATE (sps)

		2400	2743	2800	3000	3200	3429
DCE RATE KBPS	2.4	7.5	-	-	-	-	-
	4.8	10.0	10.0	10.0	10.0	10.0	9.5
	7.2	12.5	12.5	12.5	12.5	12.0	11.5
	9.6	16.0	15.5	15.5	14.5	14.5	13.5
	12.0	19.0	17.5	17.5	17.0	16.5	16.5
	14.4	22.0	20.0	20.0	19.5	19.0	18.5
	16.8	25.0	23.0	23.0	21.5	21.0	20.0
	19.2	28.0	25.5	25.5	24.0	23.5	22.5
	21.6	32.0	28.5	28.0	26.5	25.5	24.5
	24.0	-	31.0	31.0	29.5	28.5	26.5
	26.4	-	[redacted]	[redacted]	31.5	30.5	28.5
	28.8	-	-	-	[redacted]	33.5	31.0
	[redacted]	-	-	-	-	[redacted]	[redacted]
	[redacted]	-	-	-	-	-	[redacted]
Modem Bandwidth (Hz)		400-2800 600-3000	274-3018 457-3200	280-3080 467-3267	300-3300 500-3500	229-3429 320-3520	244-3674

* For a well designed modem in the presence of Random Noise (dB) and a BLER of 0.01

The important thing to note is how high the SNR requirement is at the higher DCE connect rates. A difference of several dB can prevent a modem from connecting at its highest rate.

It is important to note that network echoes can be significantly dispersed by attenuation distortion and/or envelope delay distortion. This can result in pre-and post cursors that fall outside the modem echo canceller's span. The uncancelled cursors appear as signal dependent noise to the modem. Since most modems utilize 600 ohms[3] and every loop has a different impedance, in most

[3] 600 Ohms was chosen by modem manufacturers primarily because modems are tested on test equipment with 600 Ohm terminations.

cases, there is an inherent impedance mismatch between the modem hybrid and the local loop. This strong near "talker echo" is adequately canceled by most modems.

5. PSTN Impairments Affecting Modem Performance

PSTN impairments that affect modem throughput are illustrated below in Figure 3:

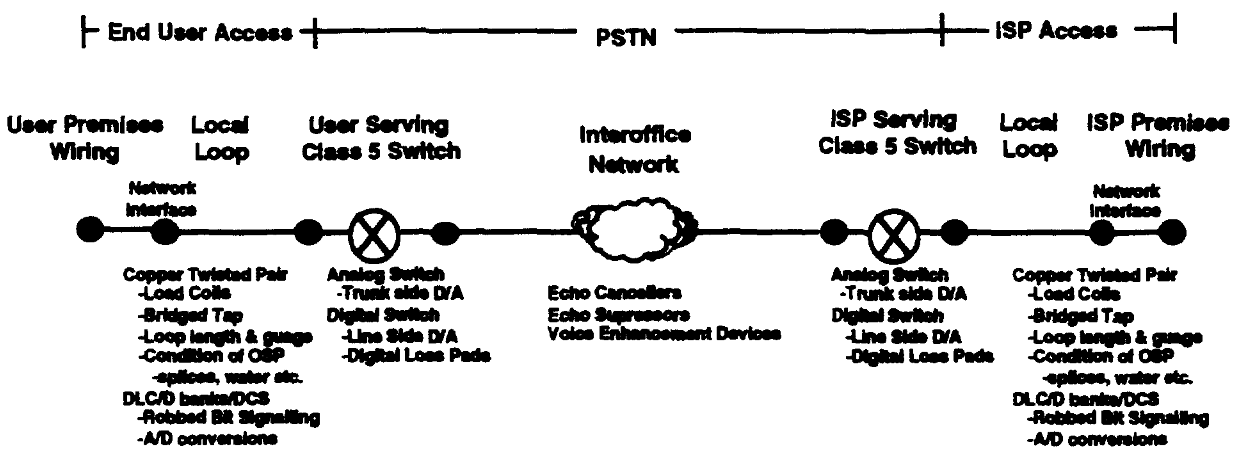

Figure 3: PSTN Factors Potentially Affecting Modem Performance

5.1 Signal Level Impairments

Analog impairments can limit a modem's performance. In today's PSTN, the dominant analog impairments are found in the copper wire portion of the circuit (although analog switches and trunks can be additional sources). The three primary impairments are attenuation, attenuation distortion and noise. Most modems have been designed to overcome analog impairments due to attenuation and attenuation distortion. Other analog impairments are found in the filters present in line cards or channel units that the local loop connects to.

Table 3 summarizes the signal level impairments. The table is divided into two sections: the heavily outlined section represents impairments that have a serious impact on modem performance and the dashed section includes impairments that should not affect V.34 performance at 28.8kb/s (they may, however, affect performance at higher rates).

Table 3: Summary of PSTN Signal Level Impairments

Network Equipment	Network Location(s)	Attenuation	Impairment	Some Remedies
Long Copper Loops	POTS Lines	Very Wide Range e.g, 11 dB for 10 kft at 3700 Hz	Signal attenuation. Attenuation distortion .	Access Service like ISDN Use a DLC System.
Load Coils	Loops>18kft and some shorter loops serving business premises or left over from a wire center transfer.	5 dB/Load 24 AWG 3700 Hz	Limits usable bandwidth at high frequencies.	Remove Load Coils if <18kft. Use Digital Loop Carrier System
Bandpass Filters	Analog & digital channel units Switch Line Cards Analog Line Conditioning Equipment	>= 4 dB at 3700 Hz per CODEC	Limits usable bandwidth	Effects accumulate with number of line cards to limit highest connect rates.
Digital Loss Pads	Digital Switches	0 dB, 3 dB or 6 dB	Limits usable bandwidth	
Analog Loss Pads	Channel units Switch Line Cards	0-5 dB	Used to reduce levels on short loops.	Usually not a problem for modems

5.1.1 The Local Loop

Every PSTN connection has some length of copper wire connecting the modem to the network. The length of a wire pair can vary from several hundred feet to over six miles. Figure 4 is an example of a typical metallic loop. Note that the cable is "multipled" to two Serving Area Interfaces (SAIs) but is only jumpered to connect to a single subscriber. The additional legs of cable (bridged tap) on the pair that are not terminated contribute to loss and create reflections, however modems can usually cancel them. Longer loops (>18kft) have load coils at regular spacings. Load coils improve voice transmission but limit the effective usable bandwidth of the channel. (Note that load coils may, at times, be found scattered throughout shorter loops due to past plant engineering practices.)